Physics
OSAKA UNIVERSITY

科研費
KAKENHI

Generation of Twisted Gamma-Rays Using Accelerated Ions

Minoru Tanaka (Osaka U)

In collaboration with
Noboru Sasao (Okayama U) and Motomichi Tashiro (Toyo U)

Ann. Phys. (Berlin) 2022, 2200168. arXiv:2203.06988

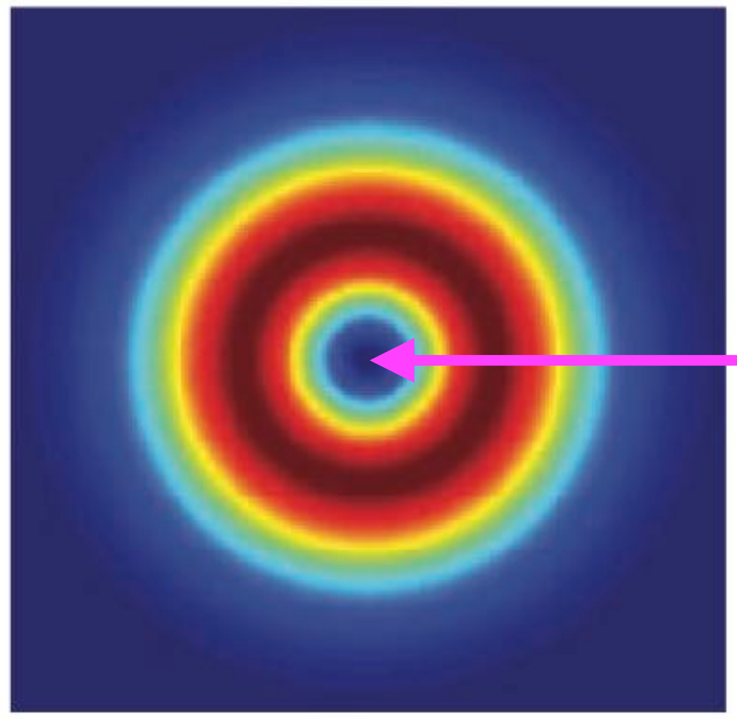
MMQS2022, Mie University, 2022/12/8

Twisted photon(捩光子), optical vortex(光渦)

Orbital angular momentum (OAM) of light

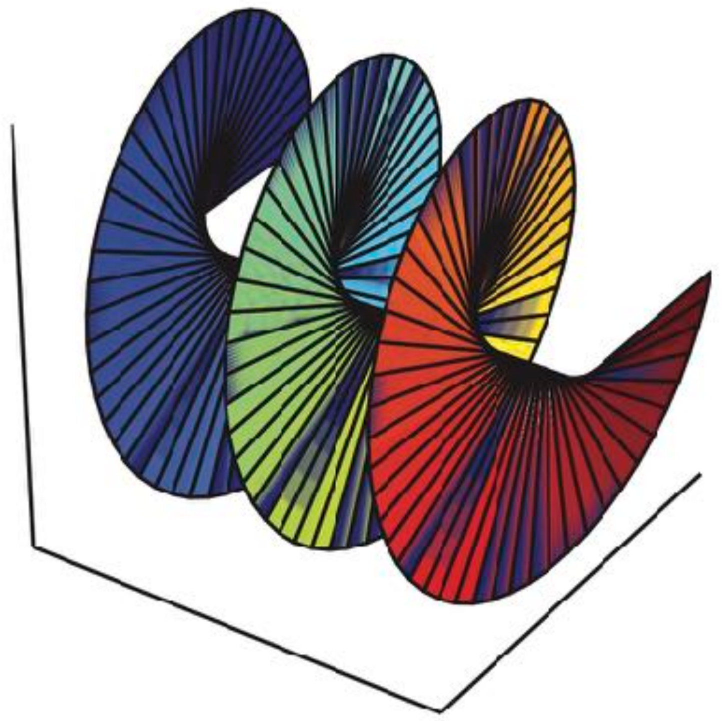
winding field phase ~ $e^{im\varphi}$

G. Molina-Terriza et al. Nat. Phys. 3, 305 (2007)



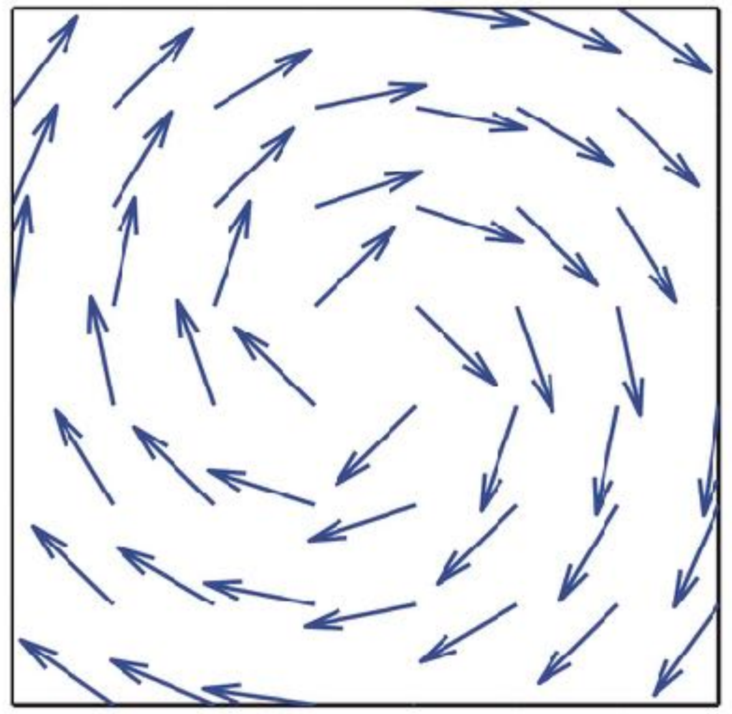
field intensity

phase singularity

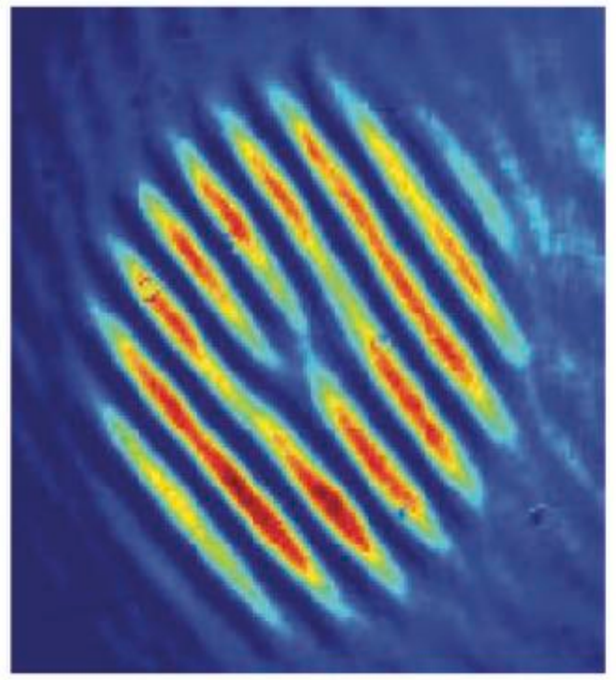


wave front

helicoid



transvers Poynting vector



Interference patter with plane wave

computer-generated hologram

Generation (and use) of twisted photons

Optical region

fork hologram, lens-based mode converter, etc.

(micro manipulation, imaging, data transmission, etc.)

Y. Shen et al., Light: Sci. & App. 8, 90 (2019)

X-ray region

helical undulator, FEL

S. Sasaki, I. McNulty, PRL 100, 124801 (2008)

E. Hemsing et al. Nat. Phys. 9, 549 (2013)

Gamma-ray region (proposals)

backward Compton scattering

$$e + \gamma_{\mathrm{tw}} \to e + \gamma_{\mathrm{tw}}$$

U.D. Jentschura, V.G. Serbo, PRL 106, 013001 (2011)

nonlinear Thomson scattering

$$e + \gamma_{\mathrm{pw/tw}} + \gamma_{\mathrm{pw/tw}} + \cdots \to e + \gamma_{\mathrm{tw}} + \cdots$$

Y. Taira, T. Hayakawa, M. Katoh, Sci. Rep. 7, 5018 (2017)

Y.-Y. Chen et al., Phys. Rev. Lett. 121, 074801 (2018)

Y.-Y. Liu et al., Opt. Lett. 48, 395 (2020)

Gamma factory

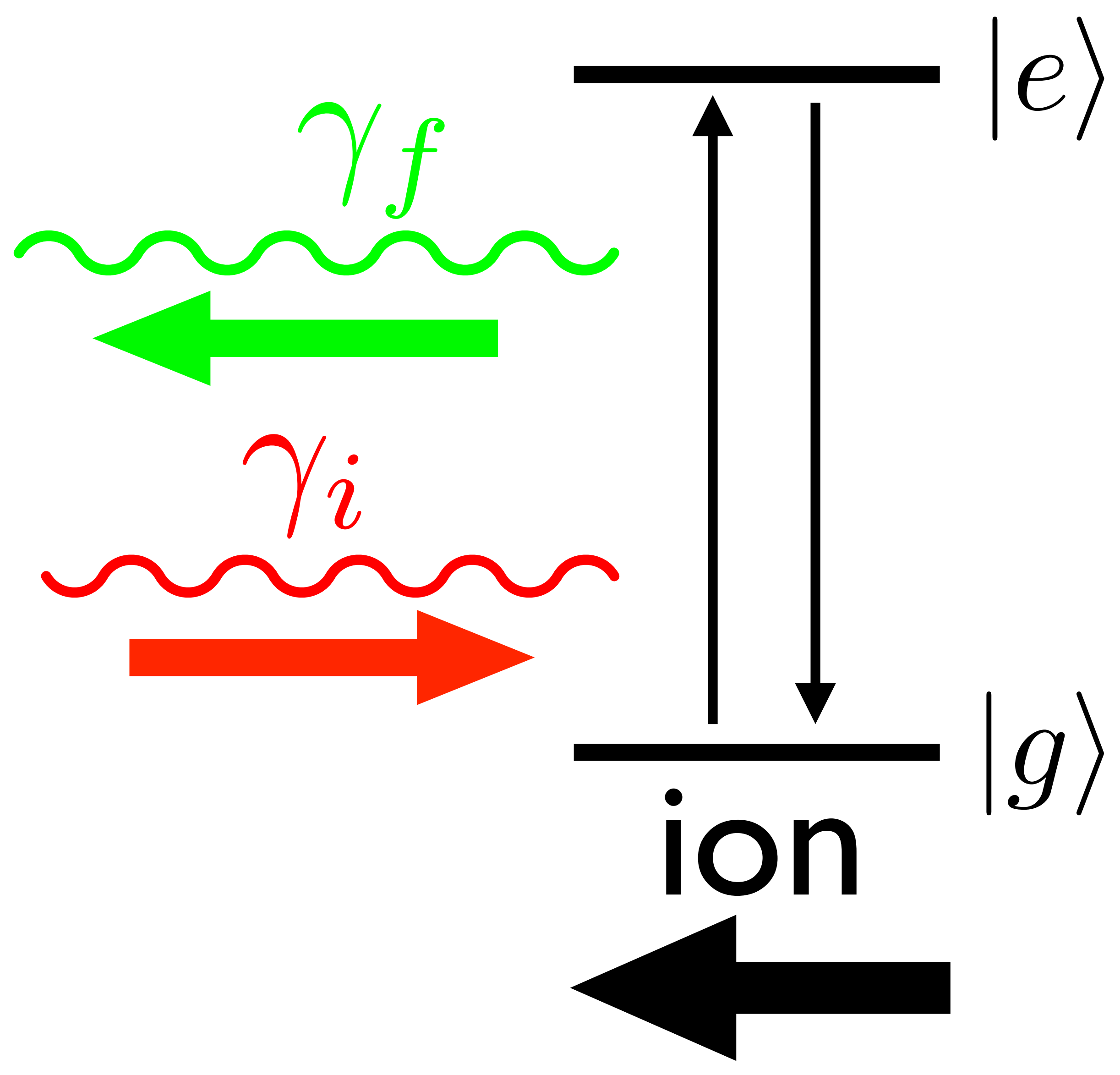
E.G.Bessonov, NIMB 309, 92 (2013)
M.W. Krasny, CERN-SPSC-2019-031; SPSC-I-253

Rayleigh scattering by boosted ion

$$\gamma_i + |g\rangle \to |e\rangle \to |g\rangle + \gamma_f$$

Lorentz boost $E = \gamma M$

e.g. $\gamma \sim 10^3$ @LHC



Level splitting: E_{eg}

binding energy of H-like ion $= (Z^2/n^2) 13.6\ \mathrm{eV}$

Resonance condition: $2\gamma\omega_i \simeq E_{eg}$ $\omega_i \sim$ 1-10 eV

$\longrightarrow$ $Z^2/2\gamma \sim$ 0.1-1

heavy ion

Up-conversion:

$$\omega_f^{\max} \simeq 2\gamma E_{eg} \simeq 4\gamma^2\omega_i \sim 0.1\text{-}1\ \mathrm{GeV}(2\gamma/10^4)^2$$

Twisted photon generation by 2γ excitation

Excitation to a state of large angular momentum

2γ absorption $\gamma_{\rm pw} + \gamma_{\rm pw} + I \to I^*$

Raman process $\gamma_{\rm pw} + I \to I^* + \gamma_{\rm pw}$

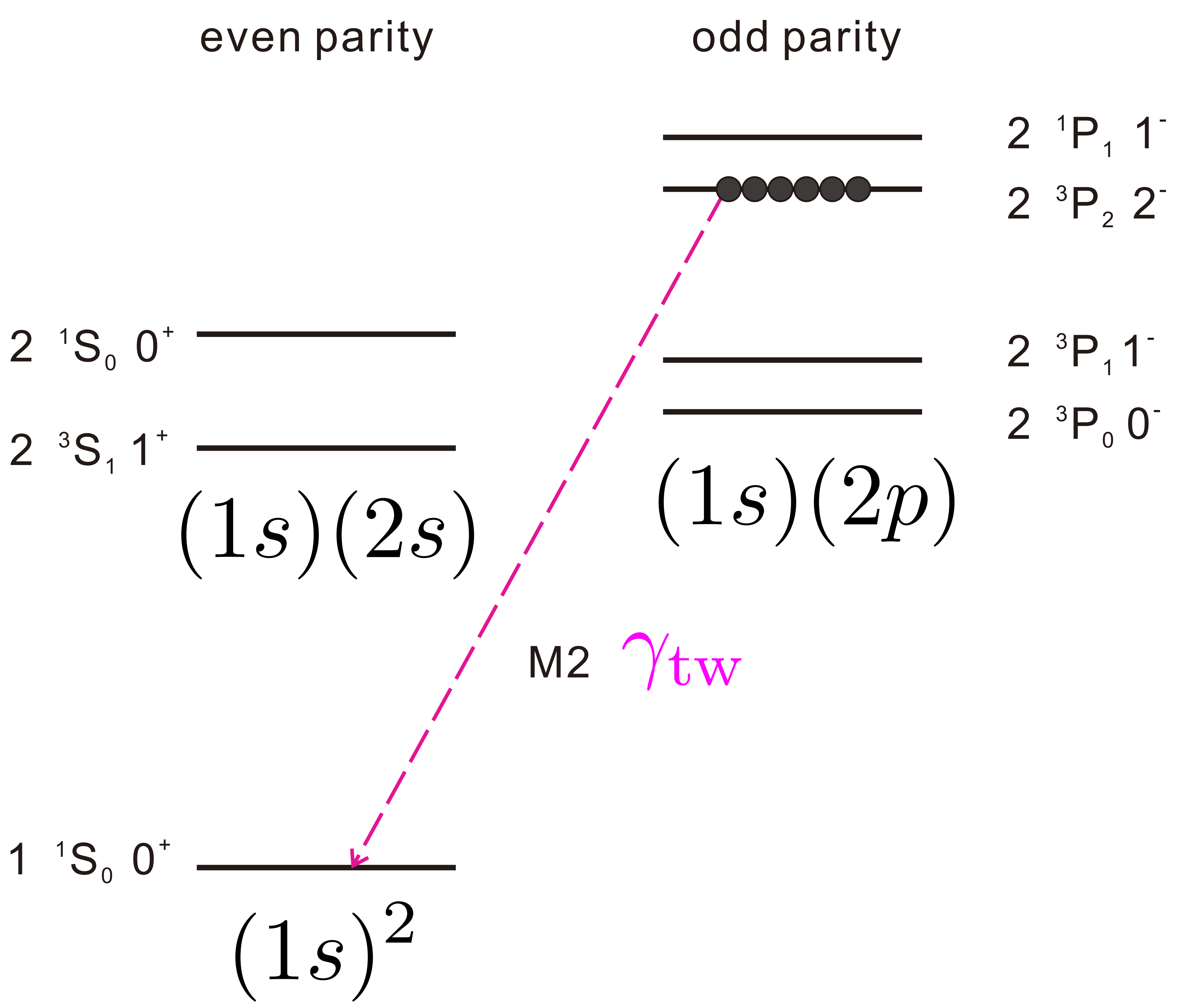
Efficient population transfer
by Stimulated Raman Adiabatic Passage (STIRAP)

Twisted photon generation in de-excitation

$I^* \to I + \gamma_{\rm tw}$

He-like ions considered

Twisted photons from He-like ions



$$(1s)(2p)\,{}^3\mathrm{P}_2 \to (1s)^2\,{}^1\mathrm{S}_0 + \gamma_{\rm tw}$$
$$(m = 2)$$

M2 transition dominates.

$\propto Z^8$ heavy ions

Kr (Z=36), Xe (Z=54) studied

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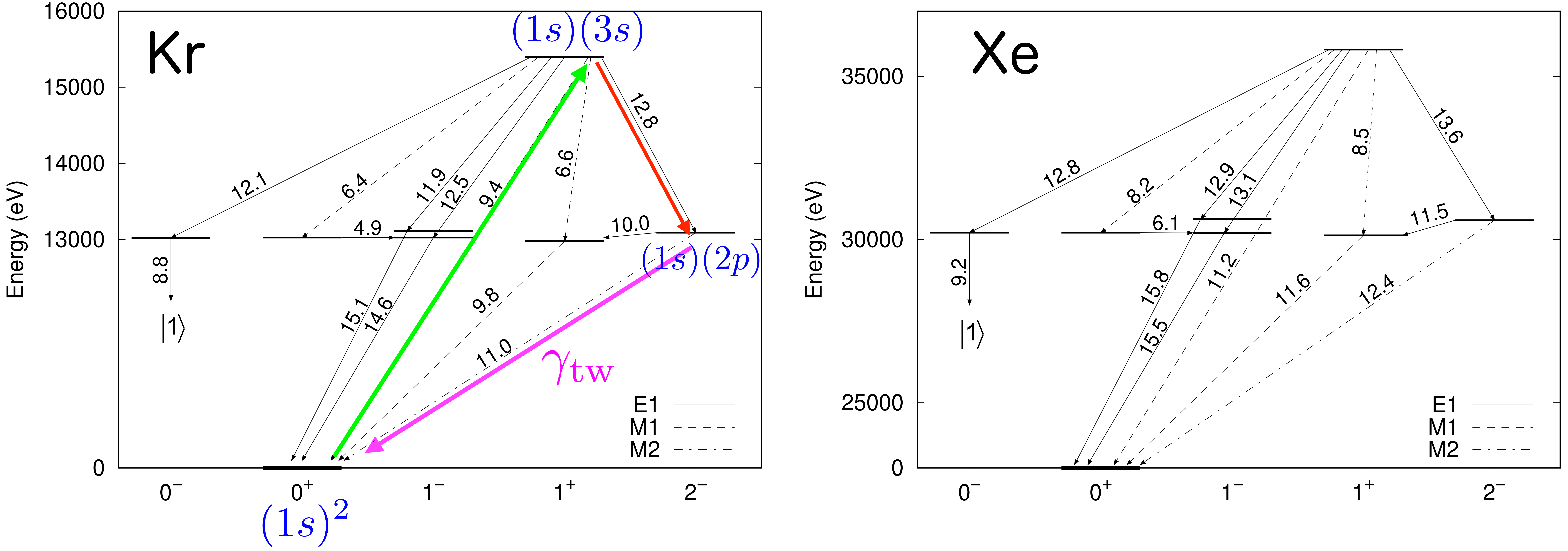
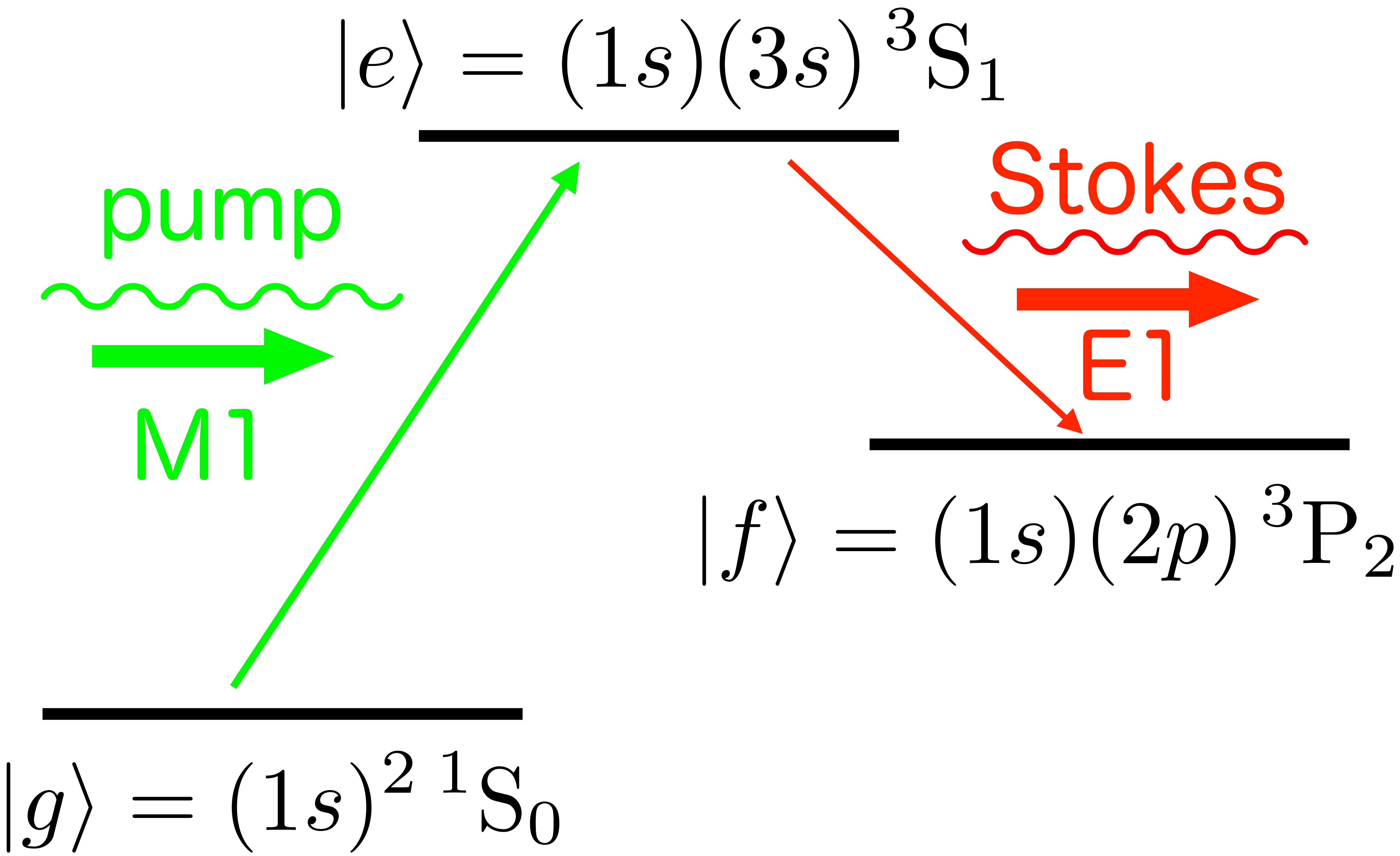
Levels and transitions of He-like ions

Calculation by GRASP2018 (MCDHF+RCI)



$E_{\gamma_{\rm tw}} = 65.4\ {\rm MeV}\ (\gamma_{\rm ion} = 2500)$ $E_{\gamma_{\rm tw}} = 306\ {\rm MeV}\ (\gamma_{\rm ion} = 5000)$

Excitation scheme by STIRAP



Rabi freq. for 1W/mm^2

	Transitions	Type	Kr [s^{-1}]	Xe [s^{-1}]
Ω_p	$\|g\rangle \to \|e\rangle$	M1	5.570×10^4	1.276×10^5
Ω_s	$\|e\rangle \to \|f\rangle$	E1	3.935×10^7	2.882×10^7

pulse profile

Kr

pump, Stokes: opposite circular pol.

Outline of numerical calculation

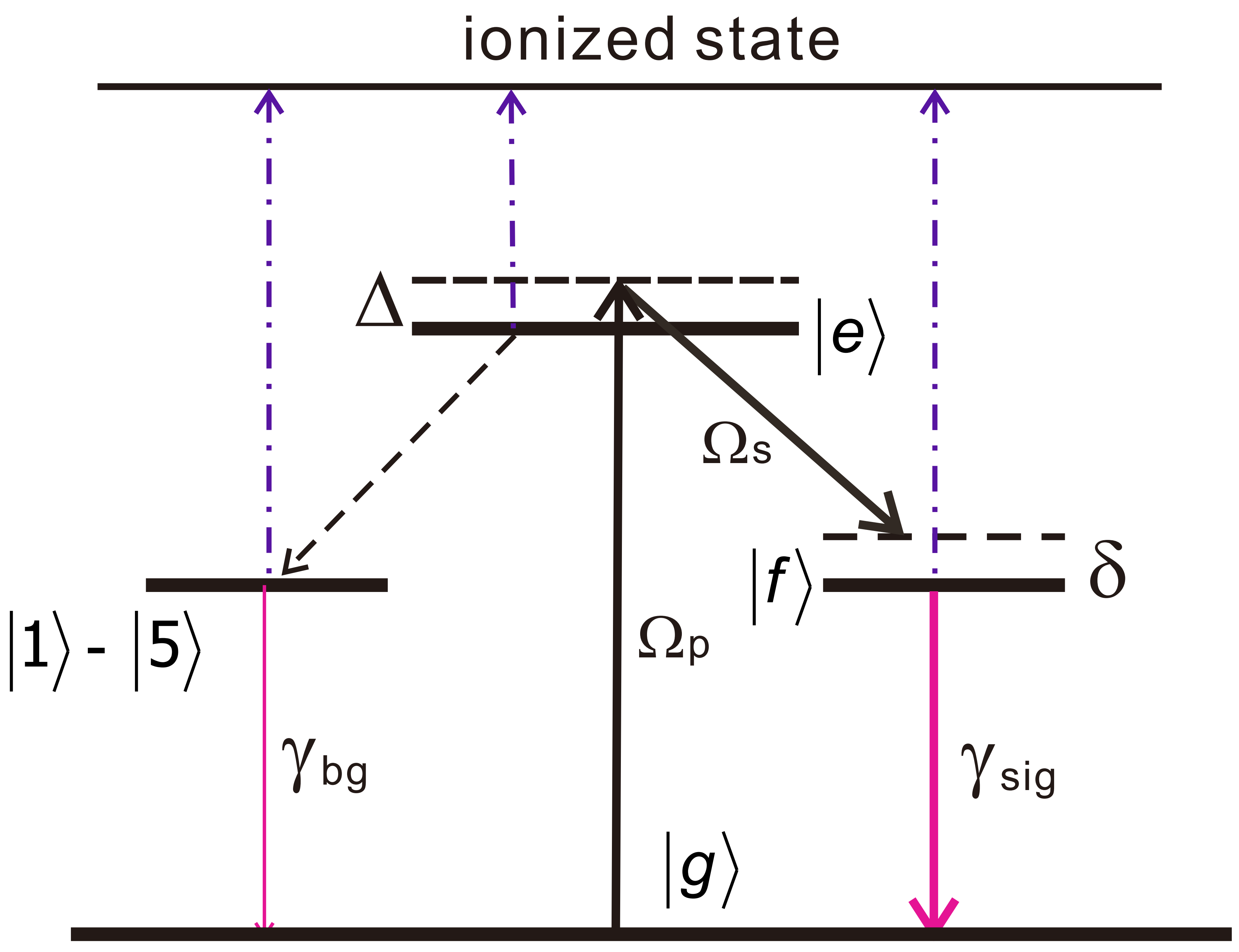
Optical Bloch Equation

$$|g\rangle = (1s)^2\,{}^1\mathrm{S}_0\,,\ |e\rangle = (1s)(3s)\,{}^3\mathrm{S}_1\,,\ |f\rangle = (1s)(2p)\,{}^3\mathrm{P}_2$$

and all other (1s)(2s) and (1s)(2p) states involved

photo-ionization included

Parameter	Symbol	Kr	Xe	units
Lorentz boost factor	γ_{ion}	2500	5000	-
Pump laser wavelength	λ_p	403	346	nm
Pump laser intensity	$I_p(0)$	4×10^5	4×10^5	$\mathrm{W/mm^2}$
Stokes laser wavelength	λ_s	2690	2371	nm
Stokes laser intensity	$I_s(0)$	4×10^5	4×10^5	$\mathrm{W/mm^2}$
Laser pulse width	σ_L	1.0	1.0	nsec
Laser pulse delay	t_d	0.5	0.5	nsec
Pump laser detuning	Δ	5	5	$\Gamma_e^{(tot)}$
Two-photon detuning	δ	0	0	$\Gamma_e^{(tot)}$



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Results (Kr)

Population

Kr

$|f\rangle$

$|e\rangle$

$$|1\rangle = (1s)(2s)\,{}^3\mathrm{S}_1$$

Signal, background, photo-ionization

Kr

BG photons:
from other 2s, 2p to 1s

B/S=5.6 %

Ion beam lifetime due to photo-ionization~10^5 sec.
(A ring of 30 km circumference asuumed)

Results (Xe)

Population

Xe

Signal, background, photo-ionization

Xe

BG photons:
from other 2s, 2p to 1s

B/S=19.2 %

Ion beam lifetime due to photo-ionization~10^5 sec. (A ring of 30 km circumference asuumed)

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Summary

- Twisted gamma-ray from accelerated He-like ion

  STIRAP $(1s)^2\,{}^1\mathrm{S}_0 \to (1s)(2p)\,{}^3\mathrm{P}_2\,,$ M2 de-excitation

- Signal 65.4(306) MeV for Kr(Xe) of boost 2500(5000)

  10^9 ions/bunch $\to$ $2.3(5.8)\ \times 10^8$ Hz/bunch $\quad C_{\mathrm{ring}} = 30$ km

- BG and ionization loss

  $B/S = 5.6(19.2)\%\,,$ loss fraction $= 6.9(11) \times 10^{-10}$

- Prospects

  Physics applications: nuclear, astro, plasma etc.

  Comparison with electron beam